SCIENCE

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RECENT EVIDENCE FOR THE EXISTENCE OF THE NUCLEUS ATOM[1]

THE great French scientist Poincaré, just before his death two years ago, described an atom before the French Physical Society in these words:

> Each atom is like a kind of solar system where the small negative electrons play the rôle of planets revolving around the great positive central electron which takes the place of our sun. . . . Besides these captive electrons there are others which are free and subject to the ordinary kinetic laws of gases. The second class are like the comets which circulate from one stellar system to another, establishing thus an exchange of energy between distant systems.

Such an atom is a world in itself and strangely different from the kind we learned about in our text-books twenty years ago. One of the much used chemistries of that day put it in this way:

> An atom is the smallest portion of matter that can exist; it is incompressible, indivisible and in itself unchangeable.

How has this great change of view come about? How has the indivisible unit evolved into the complex microcosm we now imagine? Time would fail us to trace all the steps of the way; we will attempt only to bring out some of the considerations which have in the past three years led many of our foremost thinkers to believe in that particular type of atom which we may call the nucleus atom. This type is similar to that which Poincaré pictured except that the central body is much smaller—very

[1] Address of the vice-president and chairman of Section B, Physics, of the American Association for the Advancement of Science, at Philadelphia, December 29, 1914.

small indeed as compared with even the minute electrons which circulate about it.

We will recall first several of the discoveries which have forced us to abandon the idea of an indivisible atom. The fundamental one was Sir Joseph Thomson's discovery of the electron. In studying the nature of the cathode rays he found that they consisted of extraordinarily minute particles all exactly alike, whatever the nature of the gas within the tube might be. In a series of brilliant experimental studies he was able to show that the mass of one of these electrons was only one eighteen hundredth that of the lightest known atom. Then came Zeeman's discovery[2] that the separate lines of many spectra are broken up into two or more lines by the action of strong magnetic fields. The study of this effect made it quite certain that light radiation is caused by the rapid vibration of electrons in the luminous body. Therefore electrons must be present in very many kinds of matter—probably in all. The electrons were early proved to carry a negative charge of electricity. Soon they revealed their presence in a great variety of ways and assisted in the explanation of widely different phenomena. But the corresponding positive constituent of matter proved singularly elusive although most diligently sought for, and it is only very recently that we seem to have traced it to its hiding-place.

Different views regarding the nature of this positive constituent have led to much diversity of opinion regarding the structure of atoms. One of the most successful of these theories is that proposed by Sir Joseph Thomson in 1904.[3] He supposed a relatively large positive mass to exist—nearly as large as the atom—with the minute negative electrons distributed through it in such a way as to make the system a stable one. For easy mathematical treatment he assumed the electrons at equal distances apart in a series of concentric circular rings. To secure stability and illustrate certain atomic properties he supposed these rings to be in rotation. Thomson discussed many such configurations and satisfactorily explained many facts regarding the valency, the position in the periodic system, the electropositive or electronegative character and other chemical properties of different substances.

A modification of Thomson's atom was proposed by H. A. Wilson in 1911.[4] He supposes each negative electron to be situated at the center of a positive sphere of sufficient size to neutralize it electrically, and the atom to be made up of a group of such units, the total number being proportional to the atomic weight. In other words, Thomson's one relatively large positive mass is divided up into equal parts, each one containing a single negative electron. The mathematical development of this idea led to the result that the hydrogen atom contains eight such units. The gold atom would therefore contain about sixteen hundred of them.

In the Thomson and the Wilson atoms, the positive portion is diffused throughout nearly the whole volume of the atom, a region about one hundred millionth of a centimeter in diameter. This type of structure has accounted for many atomic properties but has not been very successful in explaining the position of the lines in light spectra caused by vibrations in the atom.

I wish to direct your attention to-day more particularly to a type of atom in which the positive charge—equal as before to the sum of the charges of the negative electrons—is highly concentrated at the center of volume of the atom, occupying only an exceedingly small part of the volume. Nagaoka[5] had discussed the stability of such an atom in 1904. Sir Ernest

Rutherford revived it in 1911 to explain phenomena observed by Geiger and Marsden,[6] and achieved a striking success. The facts observed were these; when α-rays were allowed to pass through thin sheets of metal, a small proportion of them were observed to be deflected through very large angles. Rutherford[7] made a theoretical examination of the results of a single encounter between an α-particle and an atom of the concentrated-nucleus type, and calculated the proportion of the α-particles which would be deflected through various angles by such encounters. Geiger[8] then made a new experimental study of the scattering produced by gold foil and found a very satisfactory verification of Rutherford's formula. From the amount of scattering at various angles, the value of the nucleus charge was also calculated. For gold it came out about 100 e. The general conclusion was reached that the nucleus charge is about one half the atomic weight times the charge of an electron. But Barkla[9] had earlier reached the same value for the sum of the electron charges—which in a neutral atom should equal the nucleus charge—by observations on X-rays and the use of a theory developed by J. J. Thomson. According to these views atoms contain only about one sixteenth as many electrons as they do on the theory of H. A. Wilson.

On the assumption that large angles of deflection are sometimes due to single encounters with an atom, large forces must be postulated to swing the α-particles so considerably from their paths, forces so large as to require an approach to within an exceedingly small distance from the nucleus center. This distance was calculated to be about 1/3,000 of the atom diameter. If this is true, the nucleus can hardly have a diameter exceeding 1/5,000 that of the atom.

The view that an α-particle may turn through a large angle as the result of a single encounter was strikingly confirmed in 1912 by some remarkable photographs of the paths of α-particles through a gas, taken by C. T. R. Wilson.[10] I have here a reproduction of one of these photographs which shows two abrupt bends in the trail of a particle, one of 10.5° and the other of 43°. This second bend would certainly seem to be a case of "single scattering." The astonishing conclusion regarding the small size of the nucleus has been confirmed by some recent experiments of Marsden[11] in passing α-radiation through a gas.

A theory had been worked out by Darwin that when α-radiation entered hydrogen, a few H atoms would acquire from close encounters with the α-particles a velocity 1.6 times that of the striking α-particle, corresponding to a range four times that of the radiation. Marsden's experiments were undertaken to test this theory. He passed α-rays into hydrogen and observed the scintillations on a zinc sulphide screen placed at various distances. The range of the α-particles was found to be 20 cm., but a few scintillations were found when the screen was as much as 90 cm. distant, due seemingly to the rapidly moving H atoms in their recoil from collision with the heavier α-particles. This was a striking confirmation of Darwin's theoretical calculations. Calculation by his method showed that the centers of the nuclei during collision were not over 1.7×10^{-13} cm. apart. This then would be the maximum value of the sum of their radii. This is smaller even than the former result and also smaller than the accepted value of the diameter of an electron.

Thus the nucleus of the atom appears to be extraordinarily minute, and this suggests an explanation of the somewhat paradoxical result, that practically all of the mass of

the atom seems to reside in the nucleus. For if the size is extremely small its electromagnetic mass would—from the formula $2/3 \frac{e^2}{a}$—be relatively large. So its mass might be 1,800 times that of the electron (and J. J. Thomson's experiments suggest that no positive carrier has a mass smaller than that amount) provided its diameter were only 1/1,800 that of the electron. From such consideration Rutherford[12] thinks it probable that the *nucleus of the H atom* is, in fact, the long-sought positive electron.

Attention has been forcibly drawn to the nucleus type of atom within the past year and a half by the extraordinary success it has had as interpreted by Bohr, Darwin and Moseley, in accounting for the exact position of lines in the spectra of gases. Their work has also served to bring into the limelight the earlier and perhaps equally striking work of J. W. Nicholson. In November, 1911, he published a paper[13] in which he assumed the existence of several elements with atoms of very simple and definite structure. One of these he called nebulium. In the neutral condition it was supposed to have a positive nucleus with charge 4 e, and around it at equal distances apart in a circular path, rotated four electrons each with unit charge e. It might, however, lose one electron, when it would become positively charged, its three electrons now taking up new positions a third of a circumference apart. Similarly he supposed that the atom might take up more electrons, and have a negative charge.

He discussed mathematically the vibratory motions of such an atom and showed what kind of a spectrum the radiation would furnish. The theoretical analysis of the spectrum of his imaginary element nebulium showed that all the characteristic nebula lines of the Great Nebula in Orion, leaving out those due to hydrogen and helium, could be attributed to the vibrations of the nebulium atom, except two lines. On the very day he read this paper in England a German astronomer, M. Wolf,[14] presented a paper in Heidelberg which described the discovery that different lines of this nebula were due to radiation from different parts of the nebula, and that these two lines which Nicholson had found exceptional were due to a radiating source different from that of the other lines. Whereas almost all the lines were due to radiation from the bright ring of the nebula, these two lines were caused by radiation from different parts of the nebula, that for one of them coming from the dark central space and for the other chiefly from the outer edge of the ring. All other lines had their maximum brightness in the bright ring itself.

Another imaginary substance which Nicholson named protofluorine, he succeeded in connecting in a similar way with the spectrum of the sun's corona.[15] This atom he supposes to have—when neutral—a nucleus 5 e with 5 electrons in a circular orbit about it. He analyzes its radiation on the assumption that it gives forth radiation energy in quanta, as Planck has supposed. He anticipates Bohr in the emphasis he gives to the idea of constancy of angular momentum in the rotating electrons. His calculations on this protofluorine atom account satisfactorily for the existence of fourteen out of the twenty-two lines of the corona spectrum, with an average difference of less than one part in a thousand between observed and calculated values. His calculations also show the magnitude of the positive or negative charge of the atoms originating the various lines. He concludes that in these primitive forms of matter—nebulæ and

solar corona—very simple types of atom exist, much more simple doubtless and more amenable to calculation than are the atoms of most terrestrial substances. While the correspondence between his calculated spectra and those observed at Lick Observatory is not so close as is that between theory and observed spectra in the recent work of Bohr, it is important to observe that most of these results are obtained by means of established mechanical principles and without the use of such questionable assumptions as the brilliant young Dane cheerfully and confidently makes.

And now let us consider briefly the work of Bohr. This is set forth in four papers[16] published in the *Philosophical Magazine* between July of last year and March of the present year. He starts with the Rutherford atom, *i. e.,* a minute positive nucleus with its system of electrons revolving about it, the mass of the atom resident chiefly in the nucleus and the number of electrons approximately equal to half the atomic weight. He admits the difficulty of securing stability in such an atom (as compared, for instance, with Thomson's 1904 atom), but thinks that this difficulty can be removed if we admit the insufficiency of the classical dynamics to explain phenomena involving atomic distances, and introduce Planck's quantum into the equations. He claims that this furnishes a basis not only for a theory of atomic constitution but for that of molecules as well. He differs from Nicholson radically in assuming that when in a state of uniform rotation, the electrons do not radiate. This is not in accordance with our ordinary electrodynamics. Each atom, according to Bohr, has a number of "steady states" during which the electrons revolve uniformly and there is no radiation. But in passing from one steady state to another an electron winds inward toward the nucleus with its frequency increasing. Its acceleration meanwhile causes radiation, until the electrons settle into another steady state and ceases for the time to radiate. In its stable state the angular momentum of every electron is the same. This agrees with Planck's idea of discontinuous radiation and the amount radiated in one emission for a vibrator of frequency ν is $\tau h\nu$ where τ is some integer and h is Planck's "universal constant." Bohr finds the equation for the relation between the frequency, mass of an electron, charge of electron, τ and h. When τ is made 2 in the equation, Balmer's series for hydrogen is obtained, and for $\tau = 3$ the infra-red series which Ritz anticipated and Paschen found. $\tau = 1$ gives a series of lines in the ultra-violet and $\tau = 4$ and 5 in the infra-red, neither of which has yet been observed. The lines observed by Fowler and by Pickering he connects with helium instead of with hydrogen.

From this equation he also calculates Rydberg's number N° and obtains 3.26×10^{15}. Its observed value is 3.29×10^{15}, so that the agreement of theory with observation is satisfactory. The theory further requires that very low gas density be required for numerous spectrum lines and very great gas volume for sufficient intensity. This probably accounts for the fact that 33 lines of the Balmer series for hydrogen can be seen in celestial spectra while only 12 appear in terrestrial (vacuum-tube) spectra.

From the work of Barkla, and of Geiger and Marsden on the scattering of radiation Bohr accepts the view of van der Broek that the number of electrons in an atom in the neutral state indicates the position of the element in the periodic table. Thus he gives hydrogen one electron, helium two, lithium three, beryllium four, etc. The same number expresses the magnitude of the positive charge on the nucleus.

It is difficult to pass upon the validity of

some of Bohr's assumptions. So high an authority as Jeans[17] calls it "a most ingenious and suggestive, and I think we must add convincing explanation of the laws of series spectra," and yet he adds a little later that the only justification for the assumptions Bohr makes is "the very weighty one of success." Rutherford cautiously observes:

> The theories of Bohr are of great interest and importance as a first attempt to construct atoms and molecules and explain their spectra.

The views of Rutherford and Bohr regarding the structure of atoms are strongly supported by some striking experiments of Moseley published during the past year.[18] His work utilizes the methods worked out by W. H. and W. L. Bragg[19] for measuring the spectra obtained by reflecting X-rays from the faces of crystals. Barkla and Sadler[20] showed in 1908 that if X-rays from an ordinary tube fall on different metals, "characteristic X-rays" are given off—these being different for each metal. Many metals can give out at least two different types of radiation. Barkla called these the "K series" and the "L series" radiations. For each metal the "K" radiation is about 300 times as penetrating as the "L" radiation. Kaye[21] has shown that an element excited under suitable conditions by rapid cathode rays gives out a considerable portion of the X-rays produced in the form of characteristic rays.

Moseley photographed the spectra obtained by using a great variety of different metals as targets for cathode-ray bombardment. The X-rays so produced were reflected from a crystal face and then fell upon the photographic plate. Spectra of the third order showing fine sharp lines were obtained. Similar results were secured for over forty metals. For the elements of lower atomic weights, each spectrum showed two prominent lines, and the spectrum of any element was almost exactly like that of the element next below it in the periodic table except that it was shifted in the direction of shorter wave length by about the distance between its two lines. The radiation was of the "K" type. Thus a close relation was established between the X-ray wave-length and chemical properties. Further, the frequency of the principal line was found to be proportional to $(N\text{-}a)^2$, where N is an integer and a is a constant equal to about unity. N is called the atomic number of the element. Thus is it 20 for Ca, 22 for Ti, 23 for Va, 24 for Cr, 25 for Mn, 26 for Fe, 27 for Co, 28 for Ni, 29 for Cu, 30 for Zn, etc. These numbers are very nearly in the orders of the increasing atomic weights, but more exactly in the order of Mendeleeff's periodic table. The numbers then correspond with the changes in chemical properties more nearly than do the atomic weights. For instance, we have Fe, Co, Ni representing both the chemical order and order of the atomic numbers (26, 27, 28), while Fe, Ni, Co is the order of increasing atomic weights. It thus appears that this atomic number is a more fundamental quantity than is the atomic weight, or as Soddy[22] has put it,

> It is the nuclear charge rather than the atomic mass, which fixes the position of the element in the Periodic Table.

A. van der Broek[23] had before this suggested that the total number of unit charges on the electrons of an atom is the number representing the position of the element arranged according to increasing atomic weight. But in a neutral atom the sum of the (negative) charges on the electrons should equal the positive charge on the nucleus, so that the two statements amount to the same thing.

When the experimental values found for the frequency were compared with those

indicated by Bohr's theory, the agreement was found to be a remarkably close one.

With elements of higher atomic weight Moseley obtained spectra whose lines indicated the Barkla "L type" of radiation. The atomic numbers calculated from the positions of the strongest lines of these "L" spectra ranged from 40 for zirconium to 79 for gold. These experiments then give strong support to the hypothesis of van der Broek that the total charge of the electrons of an atom indicates its position in the periodic system. Known elements were found to correspond with all the numbers from 13 to 79 except three, indicating that three elements probably remain to be discovered. The wave-lengths of the characteristic X-rays from the metal is of the order of 1/1000 that of visible light (*i. e.*, about 40 waves in .000001 inch).

During the past few months Rutherford and Andrade[24] have extended these methods of crystal reflection to the study of radiation from Ra-B Ra-C. The γ-ray spectrum of Ra-B was found to be of the same general type as that of the X-ray spectrum from various heavy metals when bombarded by cathode rays. The result for soft γ-rays from Ra-B shows that its radiation belongs to the "L series" for heavy metals. Moseley's formula applied to the measurement of the lines of the γ-ray spectrum gave $N = 82$, which is the atomic number of lead. The atomic weight of Ra-B is, however, 214, while that of lead is 207. This difference is nevertheless fully explained by a new generalization of Soddy and Fajans which we will presently notice. The experiments described in the second paper were made with much more penetrating γ-radiation from both Ra-B and Ra-C. This penetrating γ-radiation from Ra-B was found to correspond to the K series for the same metal, lead. The still more penetrating radiation from Ra-C has a line spectrum of still higher frequency than the K type, for which the name "H" series is suggested. These rays are especially interesting because they have by far the shortest wave-lengths yet known, only about 1/8 of the wave-length of the shortest X-ray waves measured by Moseley or about 1/80,000 of the wave-length of sodium light. Rutherford in his comments on these waves very justly remarks, "It is surprising that the architecture of the crystals is sufficiently definite to resolve such short waves."

During 1913 some remarkable work on the relations of radioactive substances to each other has given support to the nucleus atom from an unexpected quarter. Fleck,[25] Russell,[26] Von Hevesey,[27] Fajans[28] and Soddy[29] have all had a share in this work. They have found that when a radioactive substance ejects an α-particle a substance of different chemical properties and different valency results. The new substance lies two columns to the left in the periodic table, has an atomic number two less and an atomic weight about four less than the parent substance. If however the radioactive substance ejects a β-particle or electron, the new substance is one column to the *right* in the periodic table, increases one in atomic number, and does not change in atomic weight. Plainly then two or more elements may occupy the same position in the periodic table, for if an element loses in succession—in any order—two β-particles and one α-particle, its atomic number will be again the same as it was at first. Thus Ra-D has the atomic number 82; it loses a β-particle and becomes Ra-E with atomic number 83; this loses another β-particle and becomes Ra-F with atomic number 84; this finally loses an α-particle and becomes lead, with the original atomic number 82. The series Ur1, Ur X 1, Ur X 2 and Ur2 is of the same kind, except that the particles are ejected in the reverse

order, α, β, β. So the old difficulty of finding places in the periodic table for the 34 radioactive substances now known has disappeared, since they have but ten different atomic numbers and require therefore but ten places in the periodic table. Soddy has introduced the term isotopes to designate two elements occupying the same place in the table. Isotopes are chemically inseparable and probably have identical spectra, but they have different atomic weights.

It is evident that much remains to be done before we have very definite ideas of the structure of the nucleus atom. Many questions are entirely unanswered. For example, in how many rings do the electrons lie? For hydrogen and helium as for nebulium and protofluorine (if they exist) the electrons are so few that they doubtless all lie in one ring, but there are reasons for believing that in atoms of higher atomic weight there are two or more rings. With a large number of electrons present—with the 100 electrons of the gold atom for instance—there may indeed be several configurations which will satisfy the conditions of stability. Even for comparatively light atoms Bohr[30] supposes that as many as five rings exist. Again from what part of the atom of a radioactive substance do these ejected α- and β-particles come? Soddy[31] believes that both originate in the nucleus, but that the chemical and the electro-chemical properties are controlled by the outer ring of the electrons. Moseley regards the similarity of the X-ray spectra of different metals as satisfactory evidence that such radiation originates inside the atom, while light radiation is determined by the "structure of the surface." Rutherford[32] and Bohr both raise the important question whether atomic nuclei contain electrons, and both conclude that they do. These and many other questions have already been asked but only tentative and provisional answers have thus far been given. Doubtless there is a field here for much important experimental and theoretical work in the immediate future—a field which American physicists will seek to cultivate with their European brethren, who have done about all of the work thus far.

These hasty considerations perhaps suffice to show the varied character of the lines of evidence that have been developed during the past three years to give support to some form of nucleus atom. Radioactive phenomena, X-ray radiation and chemical properties seem to give united testimony for it. Doubtless the final type of atom has not yet been described, for it is easy to criticize the views of Nicholson, of Bohr or any other who has proposed a model, but it is probable that some form of nucleus atom will soon receive general recognition.

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ADDRESS OF THE RETIRING VICE-PRESIDENT OF SECTION F OF THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

BEFORE proceeding to the special subject of this evening's address, which will be upon the research work of the Tortugas Laboratory of the Carnegie Institution of Washington, your retiring vice-president begs permission briefly to plead the cause of the Zoological Section of the American Association for the Advancement of Science.

Our grandfathers founded this association and during our fathers' day, in that tense period wherein the foundations of established beliefs seemed crumbling into chaos before the onslaught of Darwinism, the Zoological Section of the association was a vital force in bringing order out of the confusion of doubt and fear that beset the America of the seventies.

Then, in after years, there came the special societies, zoologists, anatomists, physiologists, ornithologists, entomologists and psychologists of America; and our Section F, having lost its appeal to the investigator as a clearing house for his ideas, has sadly languished.

However, let us not forget that the British Association which two generations ago was active in forming intelligent opinion in England, once also languished from a similar cause.

Then to our British cousins there came the light of a great idea. The field of their association expanded to embrace the whole imperial realm. Great meetings were held in Canada, South Africa and Australia, and the colonies became intellectually one with the mother country in a sense never known before.

The British Association is no longer a mere gathering of scientists, it is a mighty power in preserving that world-wide sympathy with ideals of democracy and fair play upon which the very existence of Britain's vast empire must depend. For England's strength is neither in acres nor in gold, but in the hearts of her sons who toil at many a stubborn task in many a distant land.

As servants of civilization, let the members of our own association meet the millions of America in a similar spirit.

At these meetings, let us speak with rather than to our countrymen.

Too often we may have looked upon the public as something colossal, crude and struggling, something far and apart from